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A FINITE ELEMENT ANALYSIS OF THE INFLUENCES OF ULTRASONIC WELDING PARAMETERS ON TEMPERATURE RISE AT INTERFACES OF ALUMINUM STRANDS IN WIRE BONDING PROCESS

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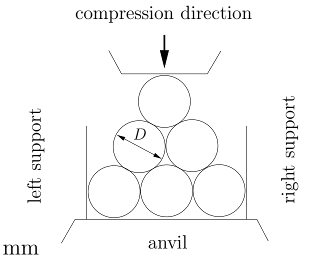
Abstract. Wire bonding is an unavoidable step in automotive industry. Multi-strand aluminum cables are used as battery cables integrated in a contact system in automobiles. Ultrasonic welding (USW) of metals is a joining technique as a combination of applying pressure and frictional vibrations within the range of ultrasonic frequencies. In automotive industry, ultrasonic welding is often used for wired connections.
The present work investigates the USW of a bundle of wires and focuses on the influence of some of the ultrasonic welding parameters, such as applied pressure on the wire bundle and vibrational amplitude of the sonotrode, on the temperature rise at the interfaces of each two strands in contact. Microsections obtained during experimental investigations show the softening of aluminum strands at some bonding parts within the wire bundle [1]. This phenomenon can be an interpretation of a local temperature rise close to the melting point of aluminum. The obvious difference in microsections from different weld samples was a motivation for this study to further investigate the thermomechanical aspects of the problem by use of finite element simulations. The represented model is a simplification of the real case and is intended to investigate the temperature rise between strands in connection during ultrasonic welding process.

1 INTRODUCTION

Wire bonding is an unavoidable production step in electronics as well as automotive industry. It is used for the connection of different electronic components and electrical centers in automobiles. Multi-strand aluminum cables are used as battery harnesses inside cars. As an alternative for crimping technology in wire bonding, ultrasonic welding is applied, which is counted as a rapid manufacturing process in order to create solid state joints between same or different materials at low temperature and low energy consumption compared to other common welding processes, such as oxy-fuel welding and arc welding. In the process of ultrasonic welding extreme thermal loading of mating parts is not applied as in many common welding processes. A combined effect of frictional and plastic heat fluxes and heat dissipations is a source for temperature rise in USW bonding mechanism in general. Based on this combined mechanism and at a specific point, freshly exposed metal surfaces will achieve a metallurgical bonding due to close atomic proximity [2]. De Vries [3] and Elangovan et al. [4], analytically computed the heat generation by friction and plastic deformation separately rather than considering the dynamic thermomechanical process .An ultrasonic welding machine consists of diverse parts, such as a pneumatic cylinder, a piezoelectric converter, a booster and a sonotrode. During ultrasonic welding, pressure is applied on the mating parts via the sonotrode, which also vibrates on top of the parts with an ultrasonic frequency of 20kHz and higher in a subsequent step. The duration of the whole process varies from some milliseconds up to a few seconds depending on the material and the dimension of the mating parts. Despite of the simplicity of the USW process, choosing the right parameters for the process in order to obtain a good quality and long lasting bond is a comlicated task, which has been under investigations for decades. In this study microscopic observations are conducted to investigate the interfacial joining of thin aluminum strands in so-called multi-strand single core cables. Obseravtions of the microsections of different weld samples show softening of aluminum at some bonding parts, which can be an interpretation of a local temperature rise near the melting point of aluminum. This study focuses on the infleuence of two welding parameters, namely sonotrode pressure and amplitude of the sonotrode vibrations, on the temperature distribution between adjoining thin strands during ultrasonic welding by use of finite element (FE) simulations.

2 THERMOMECHANICAL MODEL

A coupled thermomechanical analysis of a FE model is performed in this study. One simplified configuration of the real case is presented, as the numerical simulation of the real model with the real number of strands is extremely elaborative regarding computational time and convergence of the results. The presented model consists of 6 strands as shown in Fig. 1 and is constructed using 3D stress solid elements inside Abaqus as a FE software. Machine parts, such as anvil, sonotrode and side holders, are modeled as rigid bodies and their thermal gradients are not taken into consideration in this study. The sonotrode is a part in every ultrasonic welding assembly, which compresses the parts to be welded mostly from the top and vibrates with frequencies in the ultrasonic range (equal to 20 kHz for the case of this study) in a following step. Three successive steps are defined for the FE model. The first step, which represents the applied pressure of the sonotrode is limited to 10 ms. The following step describes the vibrations of the sonotrode on the top strand and lasts 200 ms. These vibrations are applied through sonotrode along the strands length. A final



$D = 0.43$ mm

Figure 1: An arrangement of 6 strands

step of cooling down, in which the sonotrode moves upward follows the process and lasts 80 ms. The compression of the mating parts through sonotrode pressure is recalculated in displacement and is applied inside the models for three different pressures, in order to investigate the influence of sonotrode pressure on the temperature rise at the strand interfaces. A downward displacement of 0.46 mm corresponds to a pressure of 1.2 bar as obtained from experiments, which is then calculated for the mentioned number of strands in the FE model. This displacement is applied through a polynomial function on the sonotrode, which is in contact to the top surface of the uppermost strand. Experiments show that the temperature rise happens largely during the second step in USW, where the vibrations are applied on the parts. To investigate this statement, three different vibration amplitudes of the sonotrode are considered, which are implemented through a sinusoidal excitation of the sonotrode with a circular frequency of 125664 cycles/seconds. A summary of the parameter study is given in Table 1. The FE model contains 55554 linear hexahedral elements of type coupled temperature-displacement.

Table 1: Defined parameters for different models

Model	Pressure in bar	Vibration amplitude in μm
Reference model	1.2	6
Model 1	1.5	6
Model 2	1.0	6
Model 3	1.2	7
Model 4	1.2	8

2.1 Theoretical approach

In the mentioned process of ultrasonic wire bonding, heat is generated due to frictional sliding of the sonotrode on the top strand(s) combined with the large plastic deformations of soft thin aluminum strands. In the presented model the generated heat is distributed to the lower strands through thermal conductivity. Transmission of heat through convection and radiation is not considered in this study. If q_f is considered as the heat flux density generated by frictional vibrations and q_c is the heat flux density due to conduction, then the heat flux densities going out the two sides of the surface in contact, q_1 and q_2 are given as [5]

$$q_1 = q_c - q_f, \quad q_2 = -q_c - q_f, \tag{1}$$

where q_f is calculated as

$$q_f = \eta \ \mu \ \tau \ \dot{s} \ . \tag{2}$$

Herein, η represents the fraction of the dissipated energy caused by friction which is converted to heat and is considered as 1.0 (100 %). The converted heat is distributed equally and instantaneously to the surfaces in contact. μ is the coefficient of friction, τ is the contact stress and $\dot{s}$ is the slip rate between the two surfaces. The contact stress is dependent on the temperatures on either side of the interface as well as the contact pressure p. The conductive heat flux density q_c, across the contact surfaces in eq. (1) is given as

$$q_c = k(h, \bar{\theta}, p) \ (\theta_1 - \theta_2), \tag{3}$$

where k is the heat transfer coefficient and is considered to be a function of the average temperature at the contact point $\bar{\theta}$, the contact pressure p and the overclosure or gap conductance h. θ_1 and θ_2 are the temperatures at the contact surfaces. The portion of the heat generated by plastic straining of the material is calculated, as the material properties of the proposed aluminum alloy are considered to be temperature dependent. To represent the coupled thermomechanical behavior of the model, the Johnson-Cook plasticity model is applied, in which ϵ^p_{eq} is the equivalent plastic strain and $\dot{\epsilon}/\dot{\epsilon}_0$ is the dimensionless term for the effects of strain rate in the constitutive model. The yield stress in this model is obtained as

$$\sigma_y = [A + B(\epsilon^p_{eq})^N][1 + C \ ln\frac{\dot{\epsilon}}{\dot{\epsilon}_0}][1 - (\theta_H)^M] \ . \tag{4}$$

Here, $\dot{\epsilon}_0$ is a reference strain rate and θ_H is given as

$$\theta_H = \frac{\theta - \theta_0}{\theta_M - \theta_0}, \tag{5}$$

in which θ_0 and θ_M represent reference temperature and melting temperature, respectively. The six material constants of the Johnson-Cook model, A, B, C, N, $\dot{\epsilon}_0$ and M are identified based on experimental data collected for the aluminum alloy EN-AW1370 [6]. The volumetric heat generation q_p due to the plastic work is considered using the specific heat of the material [7],

$$q_p = \eta \ \sigma \ \dot{\epsilon}^{pl}, \tag{6}$$

where η is the fraction of dissipated heat due to plastic deformations, which appears as a volumetric heat flux and is set to 0.9. $\dot{\epsilon}^{pl}$ is the plastic strain rate and σ is the effective stress. As the process of USW involves a strong interaction of mechanical and thermal behavior of the mating parts, thermal strains should also be considered through the following equation, which requires the thermal expansion coefficient of the material α and a reference temperature θ_0 for the thermal expansion coefficient

$$\epsilon^{th} = \alpha(\theta)(\theta - \theta_0) \; . \tag{7}$$

The reference temperature in the FE model is set to $20°C$, representing room temperature.

3 MICROSECTION OBSERVATIONS

A deep inspection of the weld zones was done through preparation of microsections of some of weld samples of 27 mm^2 cables. Figs. 2 to 4 show the weld samples with two different sonotrode pressures. Microsections show that welding with a pressure of 2.8 bar results in a good bond between strands, so that the boundary between two strands cannot be recognized (see Fig. 3, position C). Furthermore softening of aluminum at some interface places is observed in Fig. 3. With an increase in the sonotrode pressure, the temperature at strand interfaces increases, but increasing the pressure over a threshold value prevents the wires from having a sliding motion against each other and therefore restricts the temperature rise. High plastic deformation of single strands due to the applied high pressure is observed in experimental results. Figure 4 shows the deformed hexagonal microsection of the wires due to a relative high pressure. This observation is in a good agreement with the work of Ding and Kim [8, 9], who stated that a higher bond force does not result in a higher contact pressure, or higher frictional energy density, suggesting that a high bond force is not directly correlated to better wire bondability. Despite of a high pressure on the strand package, the boundaries are recognizable at almost every interface beween strands (see Fig. 4).

Figure 2: Microsection of weld sample with 2.8 bar

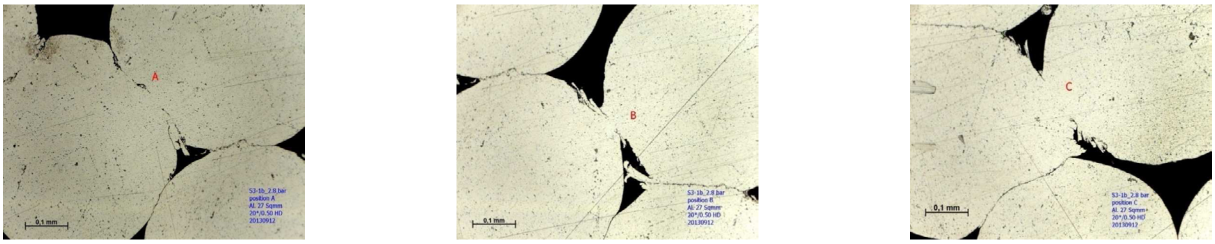


Figure 3: Magnification of positions A, B and C from Fig. 2

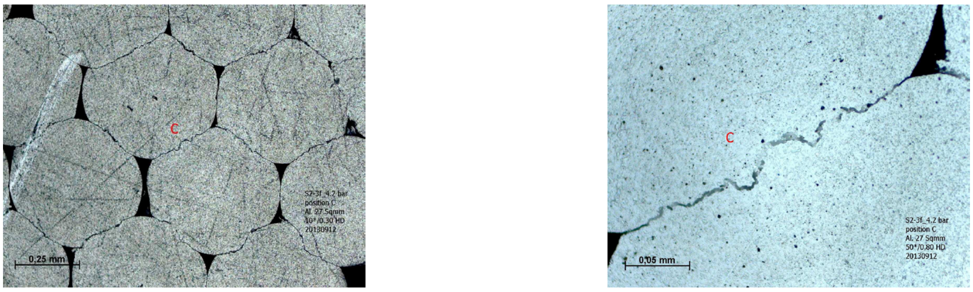


Figure 4: Microsection of weld sample with 4.2 bar (left), magnification of position C (right)

4 NUMERICAL SIMULATIONS OF THE CASE STUDY

For the numerical simulation of the case study, strands with a diameter of 0.43 mm are considered. As mentioned in Section 2, the presented FE model is a simple configuration of 6 strands. Investigation of the microsections shows that each strand during ultrasonic welding is only affected by the adjacent strands and their arrangement is an influencing factor on the final bond quality.
The experimental study of the effect of welding pressure on the bond quality was a motivation for this study to investigate the effect of welding pressure on the temperature rise at strand interfaces. In addition to that, the effect of vibrations amplitude is investigated through FE analysis.

5 RESULTS AND DISCUSSIONS

The presented results in the upcoming sections are captured at the end of the second step in the simulations, where the vibrations of the sonotrode end and before the sonotrode moves upwards.

5.1 Influence of sonotrode pressure on temperature rise at strands interfaces

The simulation results for different sonotrode pressures are shown in Fig. 5, which displays the temperature distribution along a path on the strand surfaces. The highest temperature is observed for the highest pressure, i.e. $P = 1.5$ bar. However, increasing the pressure does not increase the temperature at the surface of the bottommost strand. Furthermore increasing the pressure to 1.5 bar results in a temperature gradient of over

50 degrees at different contact places along the top strand.

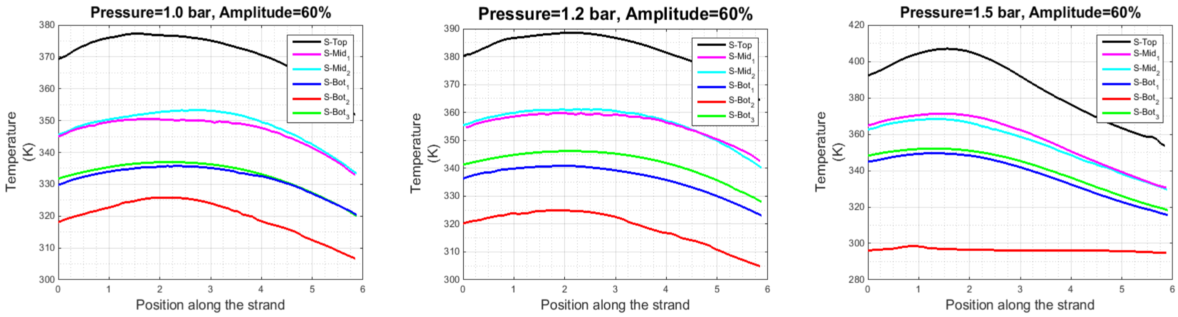


Figure 5: Temperature distribution dependency on pressure along the strand model 2 (left), reference model (middle), model 1 (right)

5.2 Influence of vibrations amplitude on temperature rise at strands interfaces

The simulations are also carried out for three different amplitudes of the vibration. Fig. 6 shows that increasing the amplitude increases the temperature at lower strands about 10 degrees. A sharp temperature drop along the top strand is not observed here and the distribution of temperature has almost the same decreasing slope for all three amplitudes.

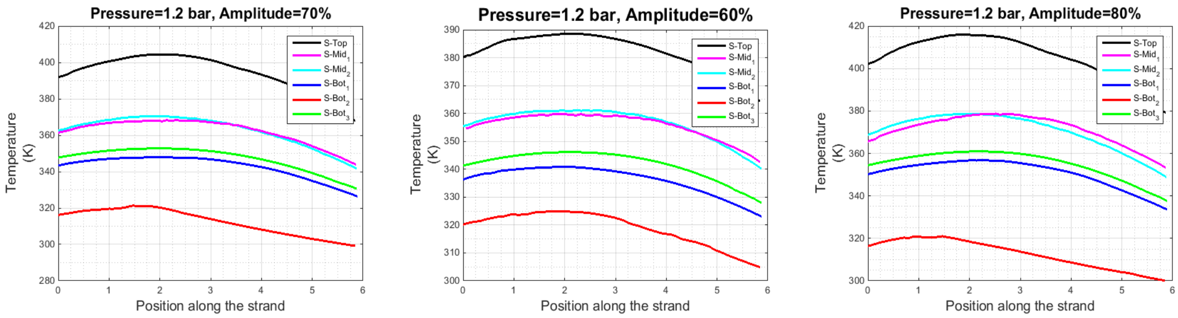


Figure 6: Temperature distribution dependency on vibration amplitude along the strand model 3 (left), reference model (middle), model 4 (right)

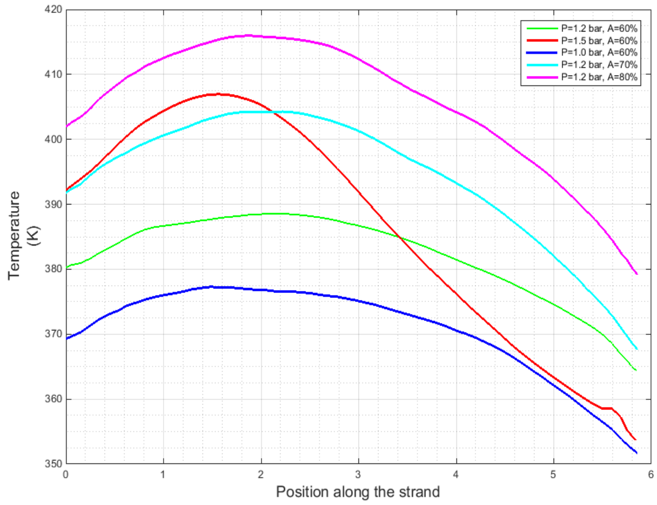


Figure 7: Temperature trend on top strand for different models

6 CONCLUSIONS

Microscopic observations as well as FE analysis of ultrasonic welding of a simple configuration of thin aluminum wires were conducted in this study. The obvious difference in microscopic pictures of weld samples with different welding prressures was a motivation to investigate the influence of pressure as an adjustable welding parameter in the process of USW on the temperature rise on the surface and between strands. Furthermore; the influence of ultrasonic vibration amplitude was also studied. As the microsections show, a higher pressure (or bonding force) results in excessive plastic deformations of the strands. This high pressure prevents the strands to rub against each other, which is the source of frictional energy and consequently generated heat at the strand interfaces. Applying a higher pressure increases the temperature at different places on the strands with a different factor. However, increasing the vibrational amplitude causes the temperature to increase in a similar pattern at almost every place on each strand surface.

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